AN ADVANCED VHF/UHF SHORT RANGE, GROUNDWAVE PROPAGATION MODEL FOR PATHS WITH NEAR-EARTH ANTENNAS

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ABSTRACT

Short range VHF and UHF paths between devices with antennas very close to, or on the earth such as: Unattended Ground Sensors (UGS) and Intelligent Munitions Systems (IMS), are attenuated above free space values by the lossy earth itself and any obstructions between a transmitter and receiver pair. Due to a paucity of measured data and propagation methods for the cases of military interest, an innovative propagation model is described that combines the seminal work of Franceschetti *et al* and Norton.

1.0 Historical Development of Ground-Wave Theories

The turn of the previous century was marked by a vigorous debate within the wireless community about how, exactly, the technology worked (Yeang, 2003). The state of affairs in the early 1900s is a good example of a technology that developed before it was well understood. Even though Marconi had successfully built and operated a string of wireless stations in Europe through the 1890s, the turn of the century dawned without any good explanation of what propagation mechanism connected those stations. The question became even more important after Marconi demonstrated trans-Atlantic wireless on December 12, 1901, between Newfoundland, Canada, and Poldhu, England, two points separated by nearly one-sixth the earth's circumference. Marconi's accomplishment raised an interesting, and unanswered, scientific question: Why did wireless waves somehow travel along the earth's surface when other similar phenomena, notably acoustic and optical waves, travel in rectilinear paths? The analogy to other wave types led to the conclusion that a wireless wave should travel in a straight line up to, but not beyond, the earth's horizon. Yet Marconi's trans-Atlantic link unequivocally demonstrated just the opposite.

Three groups of researchers grew out of the attempts to resolve this dilemma, and two competing theories were developed. Two of the groups were in Europe, emphasizing theoretical analyses of competing propagation models. The third group was in the U.S., emphasizing the engineering and empirical aspects of wireless. Fortunately for the development of both electromagnetic (EM) theory and atmospheric physics, the work of the European groups was complementary instead of competitive. In the end, the reflection theory was, in a sense, more "correct" because it explained long-distance MF and HF radiowave propagation via ionospheric reflection, which is the dominant propagation mode on long links. But for short links, especially those likely to support an UGS or IMS network, the "diffraction" theory is what led to the definitive model of ground-wave propagation.

The names of the researchers associated with this dynamic period in scientific and engineering development are well-known: in the "reflection" camp, Oliver Heaviside, Arthur Kennelly, Henri Poincaré; and in the "diffraction" camp, Jonathan Zenneck and Arnold Sommerfeld. The U.S. empiricists are perhaps less well known, but their legacy lived on for many decades in the "Austin-Cohen" formula that was published in 1911 by Louis Austin and Louis Cohen. Their formula is an empirical expression that relates signal strength to range and wavelength based on extensive U.S. Navy measurements made in 1910. The Navy data, acknowledged to be the best available, were the result of meticulously planned and executed propagation measurements and constituted the standard against which many subsequent theoretical models of wireless propagation were compared.

However, the research activities relevant to UGS and IMS links were the ones that explained short-range radio propagation, and those largely rest upon the revolutionary approach to Maxwell's equations developed by Zenneck and Sommerfeld in Germany, and, some time later, by Kenneth Norton in the U.S. While a group at Cambridge University (U.K.) made some inroads to solving the propagation-over-ground problem, notably Hector Macdonald who won the Adams Prize in 1901, it was the German group spearheaded by Arnold

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Sommerfeld that eventually provided a useful solution to the problem.

A fierce competition had developed between Marconi's team of researchers and a German group headed by Ferdinand Braun. One of Braun's colleagues was electrical engineer Jonathan Zenneck who developed a novel approach to solving Maxwell's equations: a wavelike solution that was consistent with the boundary conditions imposed by a finitely conducting ("lossy") earth.

What Zenneck discovered was revolutionary in the physics of the day, a type of EM wave never before seen. The "Zenneck wave," as it came to be known, attenuated with distance in two directions, along the surface of the earth, and perpendicular to it as well. The closest analogy at the time was free-space plane optical waves, but they did not attenuate in any direction. Another remarkable property was that the Zenneck wave's polarization was determined by the earth's electrical properties (dielectric constant and conductivity) and the signal's wavelength. This "wave tilt" predicted by Zenneck also dissipated energy in the ground as a result of circulating currents induced by the propagating signal. None of these effects had been predicted theoretically before Zenneck's previously untried and unconventional approach to Maxwell's equations.

Most of the energy in a Zenneck wave is located very close to the air-earth interface, hence the name Zenneck "surface wave" (ZSW). The ZSW decays exponentially with distance away from the earth's surface, and it attenuates with distance in the direction of propagation along the interface. Finite ground conductivity results in maximum attenuation with distance along the surface, while either zero or infinite conductivity results in no attenuation along the surface. The reason that infinite conductivity results in no attenuation is that the electric field must be perpendicular to the boundary, so that no circulating currents are induced in the ground. The reason that zero conductivity produces no attenuation is that there is no free electric charge to produce the circulating currents that create Joule heating ("$\boldsymbol{i^2R}$") losses in the earth (assumed to be a perfect dielectric with no losses, so that only displacement currents from bound charge can exist).

While the ZSW certainly was the leading candidate for theoretically explaining short-range radio propagation over the earth, it unfortunately fell short of that goal. At the time, the ZSW was a truly revolutionary insight into EM wave propagation along surfaces, but a critical element was missing – a source of radiation. Nowhere in his extensive analysis did Zenneck postulate a source with known characteristics. Instead he developed a solution to Maxwell's equations without knowing whether or not there was any way to actually create the waves he predicted, and that limitation would prove to be a very serious flaw.

Fortunately Arnold Sommerfeld, a professor of physics at the University of Munich, plugged the hole in Zenneck's theory by showing that an elemental vertically polarized radiating source ("Hertzian dipole") lying on a flat, finitely conducting surface could produce the ZSW (Sommerfeld, 1909). Sommerfeld applied a novel mathematical technique to the problem by expanding the Hertzian dipole's potential function (from which all the fields are derived) in terms of a continuous spectrum of cylindrical waves. The cylindrical waves were represented by Bessel functions of zeroth order, and the continuous wave spectrum by an integral (instead of a series) over the wave index. Sommerfeld's solution to the problem of signals propagating from an elemental dipole on a flat surface was valid for all frequencies and all values of ground electrical parameters, but still there were difficulties

The "Sommerfeld ground-wave integrals," as his form of the solution has come to be known, could not be evaluated in closed form. Even though an "exact" solution existed in the sense of an integral representation, its precise form in terms of algebraic, trigonometric, or transcendental functions remains elusive even to this day. What Sommerfeld did accomplish was an explicit asymptotic solution that showed the ZSW as a limiting solution, but one that, for practical purposes, does not matter. The conditions under which a strong ZSW is excited simply do not exist in practical antenna systems, either those of the early 1900's or today's. Thus the ZSW is an interesting theoretical construct without practical significance. To put the ZSW in perspective, however, it did point the way to Sommerfeld's formulation of the ground-wave propagation problem, and that solution is the one that does have practical significance, especially for UGS and IMS.

Perhaps the most important development in the understanding of ground-wave radio propagation is a series of papers published in the 1930s and '40s by Norton, Bullington, and Burrows. Norton's work is by far the most influential (Norton, 1937, 1941; Wait, 1995, 1998), and to this day it forms the basis of our understanding of how near-earth propagation works and how to calculate ground-wave signal levels. Norton's work was so important, in fact, that the propagation mode identified by him now bears his name, the "Norton Surface Wave" (NSW).

What Norton did was dissect the very complex mathematical formulations of Sommerfeld, van der Pol, Bremmer, Eckersley, Millington, and Gray, all well-known EM theoreticians, to develop a physical model of

ground-wave propagation that revealed its essential components and that was accessible to practicing communication engineers. Norton was the first to recognize that the ground-wave field comprises several independent components that add vectorially (amplitude and phase) to create the total field. His basic model is applicable for plane earth (but curvature can be included for sufficiently long links) at any frequency and for any values of earth electrical parameters, and it is as useful today as it was when it was first developed.

While Norton's model is mathematically complex, it is formulated so as to illuminate the underlying physical mechanisms. His equations clearly show three distinct components in the ground-wave: 1) a direct, line-of-sight signal that propagates directly from the transmitter (TX) to receiver (RX); 2) an indirect signal that reaches the RX by reflection from the earth's surface; and 3) a surface wave signal that propagates along the air-earth interface as a result of circulating currents induced in the ground. The first two components combine to create the "space wave" field, and are often referred to as the "geometric optics" field. Ground-wave signals thus consist of the space wave combined with the NSW. Norton's theory was the first to provide this insight. To achieve his goal of making his work useful in practical applications, Norton accompanied his exposition with extensive graphical data that allowed engineers to confidently design communication links across a wide range of frequencies and ground environments.

The next major step in ground-wave theory came in 1947, when Bullington extended the Norton model into the VHF range (Bullington, 1947). Norton's primary interest in the late 1930's and early '40's was MF radio (although his 1941 paper did include one example at the "ultra-high frequency" of 46 MHz). Bullington's 1947 paper provided radio engineers with a convenient and comprehensive radio link design capability in the form of several nomographs relating various system parameters: range, frequency, ground electrical parameters, and antenna heights and gains. Bullington's was the best design "handbook" available at the time, and it is still used by many today. Bullington based his work primarily on Norton's, and he provided a number of very useful approximations that reduced the complexity of Norton's formulation. As an example, Bullington introduced an approximate expression for the surface wave attenuation factor that is useful on practical radio links over a very wide range of parameters. He introduced the concept of antenna "minimum effective height," which provided a practical lower limit on antenna height that is useful for deign purposes.

Needless to say, the present day state of affairs in ground-wave modeling is quite different than in the mid part of the last century. Calculations that in 1950 would take days by hand are now routinely implemented on a hand-held calculator. The reasons for Norton's extensive graphical design data and Bullington's nomographs, namely, that the calculations were quite involved and easily prone to error, no longer are valid. Codes based on the Norton model form the basis of modern ground-wave propagation modeling. Nevertheless pitfalls still exist in implementing accurate computer-based ground-wave codes. Sommerfeld was unable to solve the ground-wave integrals in closed form, which forced him to develop approximate (asymptotic) solutions that could be written in closed form. Many cases of practical interest, however, are not amenable to an asymptotic solution, and therefore can only be solved numerically. Modern computers provide that capability, but even numerical solutions are prone to errors resulting entirely from numerical issues. With careful coding and attention to these numerical issues, modern propagation codes such as GWPL and UGSprop provide fast, accurate results that would have been impossible in Norton's day.

2.0 Architecture of the UGSprop VHF/UHF Propagation Code

2.1 Theoretical Basis

UGSprop3 is the most recent version of the UGSprop series of propagation codes designed to model radio wave propagation between nodes in an UGS network. The current model includes simplified near-earth-surface propagation models based on the Wandering Photon (WP) theory (Franceschetti *et al*, 2004; Marano *et al*, 2005) and on the Hampton semi-empirical spacewave model (Hampton *et al*, 2006). At this time, UGSprop does not include a Norton surface wave model, although a separate program (GWPL) has been developed to compute the full Norton ground-wave field (direct, indirect, and surface wave components). GWPL will be integrated with UGSprop in the near future.

The question of how to model EM wave propagation near the ground has been the subject of research for well over 100 years, yet there is no universally accepted model for typical, real-world cases. Most early models assumed a plane earth whose ground parameters were homogeneous and isotropic. In the real world that never is the case. In addition, tractable analytical models could not accommodate random distributions of the features that would impact EM wave propagation, for example, trees, buildings or vehicles. A further level of complexity arises when time-variability is introduced, in addition to random spatial variability. The fact is, near-surface propagation in real environments is a very complex problem, and even today there is no comprehensive solution. All of these considerations apply to UGS/IMS networks by the very nature of where and how they will be used. One approach to accurately

modeling near-earth propagation is to recognize from the outset its statistical nature. Many propagation models adopt that approach, with varying degrees of success. Two in particular, the Wandering Photon and Hampton models show promise for UGS/IMS and therefore are the basis for the UGSprop code being developed for CERDEC.

Radio waves, being electromagnetic in nature, exhibit the same "wave-particle" duality that light does in modern quantum physics. Sometimes light behaves in a very wavelike way, for example, the interference pattern resulting from diffraction through two parallel slits. But sometimes it is truly particle-like in its behavior, for example, in the photoelectric effect. The "photonic" nature of light is widely understood and accepted because light shows is dual nature in many common situations. But, by contrast, that same attribute is rarely associated with radio waves. The reason for this dichotomy very likely is the fact that radio waves simply do not behave like particles within the range of common, everyday experience, while light does.

One successful approach to the near-earth propagation problem has been to treat the transmitted signal as a beam of photons, instead of a wave satisfying Maxwell's equations. Each photon is a quanta of EM energy that travels along a piece-wise linear trajectory through a field of scatterers located on or near the earth's surface. The scatterers could be buildings, people, trees, vehicles, lampposts, or any object that interacts with an incident EM field. In the WP model each photon that encounters a scatterer is either completely absorbed or completely scattered (not reflected) in some random direction. The entire clutter field is characterized by two simple probabilistic parameters: average absorptivity, γ, and average scatterer lineal density (objects per meter), η.

The Hampton model differs from WP by combining an analytical spacewave model (essentially Norton's) with a semi-empirical model of propagation around corners in an urban setting. It is most applicable to that type of propagation environment, and, in fact, was developed to model military UHF communications using low-to-the-ground antennas in heavily built-up areas (soldier-soldier, UGS-UGS). Hampton's research group at the Johns Hopkins Applied Physics Laboratory did an extensive literature search for near-earth propagation models in a built-up (cluttered) environment. Between the years 1952 and 2001 a total of 12 models were published, but not a single one was applicable to the problem Hampton posed. Some of these models were physics-based, that is, resting upon first principles going back to Maxwell's equations, while others were empirical models based on measured data (typically formulas developed by regression-fitting the data). The Hampton model is a hybrid type that includes a physics-based two-ray spacewave model for unobstructed portions of the path and an empirical model for propagation around corners derived from regression-fit data. A comparison of model and measured data shows very good agreement for average field strength values, although, as would be expected, considerable fluctuation in the fields also was observed.

2.2 Implementation

UGSprop is a Windows-based executable program (EXE) that models near-earth propagation using the WP and Hampton models. All user input data are contained in a configuration (CFG) file that is user-editable. If the CFG file is not present in the EXE's directory, a default version is created by UGSprop to serve as a template for data entry. A future version of the code will support direct on-screen data entry.

A typical CFG file appears in Figure 2-1. The input data consist of two blocks, one for the WP, the other for Hampton. WP comprises two different models for propagation in different environments. The WP two-dimensional (2-D) model is applicable to open, relatively unobstructed terrain, such as grassy fields, farmland, and so on. WP's three-dimensional (3-D) model is applicable to built-up areas such as cities, military or industrial installations, and jungles or forests. The user can select the appropriate model by specifying "2-D" or "3-D" as the WP run type. The microcell radius specifies the longest range for which WP calculations are performed, since all data are presented as a function of distance from the transmitter. The two most important parameters in WP are γ and η because these quantities specify the nature of the cluttered environment. For γ, values between zero and one are possible. An absorptivity of zero means that none of the incident signal is absorbed by a scatterer, while a value of one means that all the incident energy is absorbed. Typical values based on measurements in Rome, Italy place γ in the range 0.1-0.13. For η, values between zero and infinity are allowable. A scatterer density of zero (objects per meter) means that there are no scatterers, essentially a free space environment. Indeed the WP model recovers free-space propagation (E-field falling off as the reciprocal of distance) in this case. A value approaching infinity means that the scatterers are continuous with no separation, so that no signal at all can propagate. The Rome data suggest a typical range for η in an urban setting is 0.1-0.14 (the similarity to the absorptivity range is purely coincidental). Because it perhaps is easier to think of the separation between scatterers, rather than their lineal density, UGSprop inputs this parameter as the "average distance between obstacles," which is the reciprocal of η.

The remaining parameters in the WP input section specify minimum and maximum values for γ and

η to be used in displaying three-dimensional plots of path loss and received power. By viewing path loss as a function of range and absorptivity for a fixed value of scatterer separation it is possible to visualize how sensitive the link is to variations in absorption. Likewise, displaying path loss as a function of range and scatterer density for a fixed absorptivity illuminates how sensitive the link is to how many scatterers are present.

Hampton input data comprise antenna polarization, transmitter/receiver antenna heights, ground electrical parameters, average distance to a "corner" and the loss associated with propagating around that corner, the average street width ("w2"), and the min/max ranges for calculating and displaying the link's path loss and received power. The polarization is required in the Hampton model because of the two-ray spacewave model. The received signal field strength is a strong function of polarization because the vertical and horizontal polarization plane wave reflection coefficients can be quite different. The ground electrical parameters are average values for the modeled environment. In an urban setting with asphalt streets the conductivity and dielectric constant are usually lower than in less built-up areas. Because the Hampton model was intended specifically to evaluate propagation in cities, a major feature is propagation around corners obscured by large buildings. "Turning the corner" introduces excess path loss, and that figure must be input by the user based on an estimate of its value. Similarly, the distance between the TX and the corner is important because the first part of the path is the two-ray spacewave. The street width parameter is included because the Hampton regression-fit propagation formula requires it as a parameter. Wider streets create a more open environment, and consequently lower path loss.

```
Input parameters for UGSprop3.EXE:

Run Type: 3-D
Frequency (MHz): 299.8
MicroCell Radius (meters):  500
Transmitter Power (watts):  1
Absorption Coefficient (Gamma):  0.1
Average Distance Between Obstacles (1/Eta, meters):  10
For 3-D sensitivity plots:
      Min Gamma:  0.01
      Max Gamma:  0.21
      Min Eta:    0.01
      Max Eta:    0.16

For the Hampton Model
-----------------------------
Antenna Polarization   :  VERT
[either VERT or HORZ]
TX Ant Height (meters) :  2
RX Ant Height (meters) :  2.3
Gnd Dielectric Constant:  6
Gnd Conductivity (S)   :  0.0001
Dcorner (meters)       :  106.7
Lcorner (dB)           :  6.3
w2 (meters)            :  17
Min Range (meters)     :  10
Max Range (meters)     :  500
-------------------------------------------------------
```

Figure 2-1: Typical UGSprop CFG File

Typical UGSprop output appears in Figures 2-2 through 2-5. The plots are self-explanatory, and follow the description above of how UGSprop works. To conserve space these plots are path loss versus distance. UGSprop is also capable of producing received power versus range plots for stated transmitter powers and near-earth antenna gains. In addition to the on-screen plots, UGSprop creates a data output file that contains tables of the computed values of path loss and received power.

Figure 2-2 indicates the free space (green) and obstructed (blue) path loss at 299.8 MHz between isotropic antennas in a sparse pine forest as a function of distance. Figures 2-3 and 2-4 indicate the code's ability to assist in parametric studies of the relative sensitivity to gamma (absorptivity) for a fixed value of eta (density) and vice-versa. Figure 2-5 indicates a typical path loss prediction using the Hampton formulation for specified antenna heights also at 299.8 MHz, but in an urban environment. The sharp increase in path loss at 100 meters is due to turning a corner onto another street.

UGSprop is written in PBWin8.0 (Power Basic for Windows version 8.0). It employs standard structured programming methods throughout. The program comprises a large number of individual single entry/exit point modules that are written to be as small as possible, which facilitates debugging and code modifications. UGSprop takes full advantage of PBWin's extremely efficient variable-naming convention that allows names up to 255 characters long with no penalty against run-time memory. UGSprop therefore is inherently "commented" simply by virtue of its variable names. In addition, explanatory comments are liberally added to the source code in order to clarify various aspects of the program. This approach assures continuity in maintaining UGSprop even if many different programmers become involved. In its current form, UGSprop comprises a total of 53,284 lines of executable source code, excluding comments. About 3,600 lines are for calculations, with the remainder being the Windows 32 bit Applications Program Interface (contained in the include file Win32API.inc).

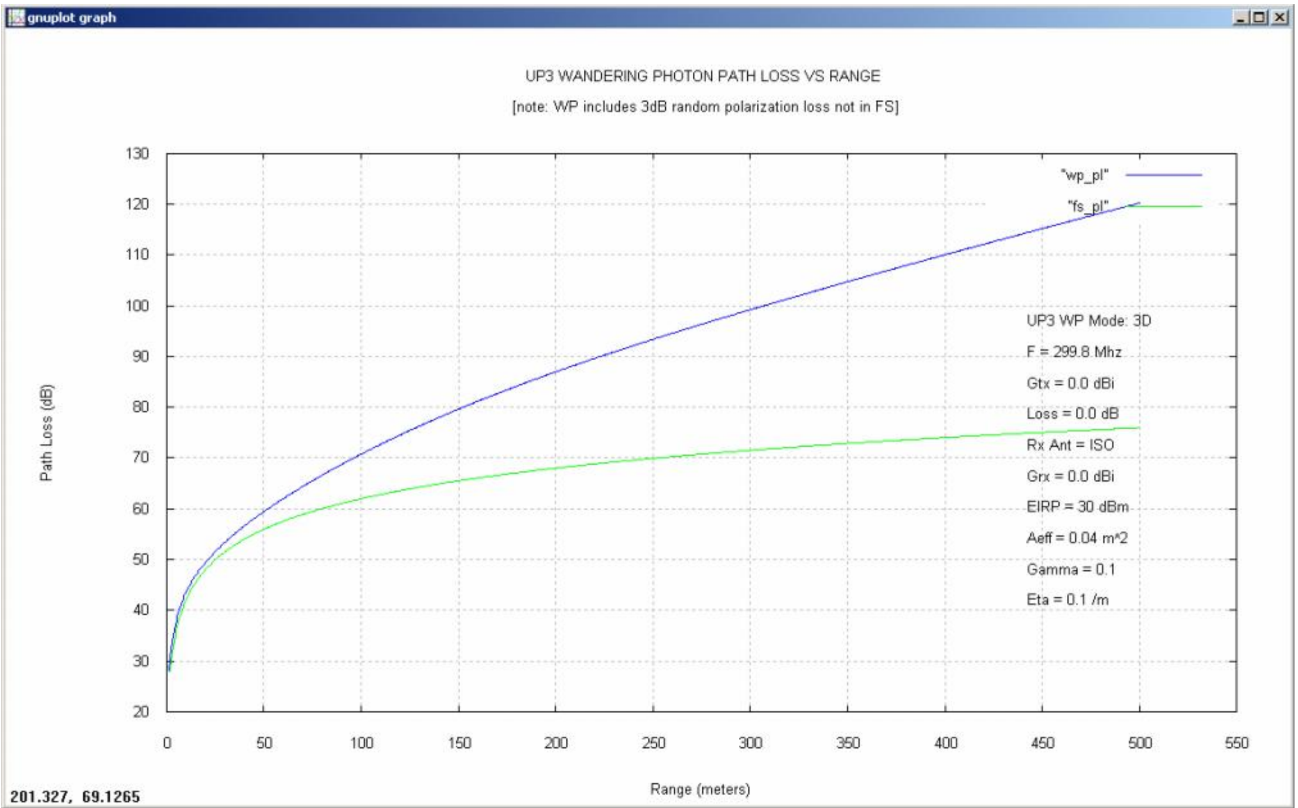

Figure 2-2: WP Path Loss vs. Range

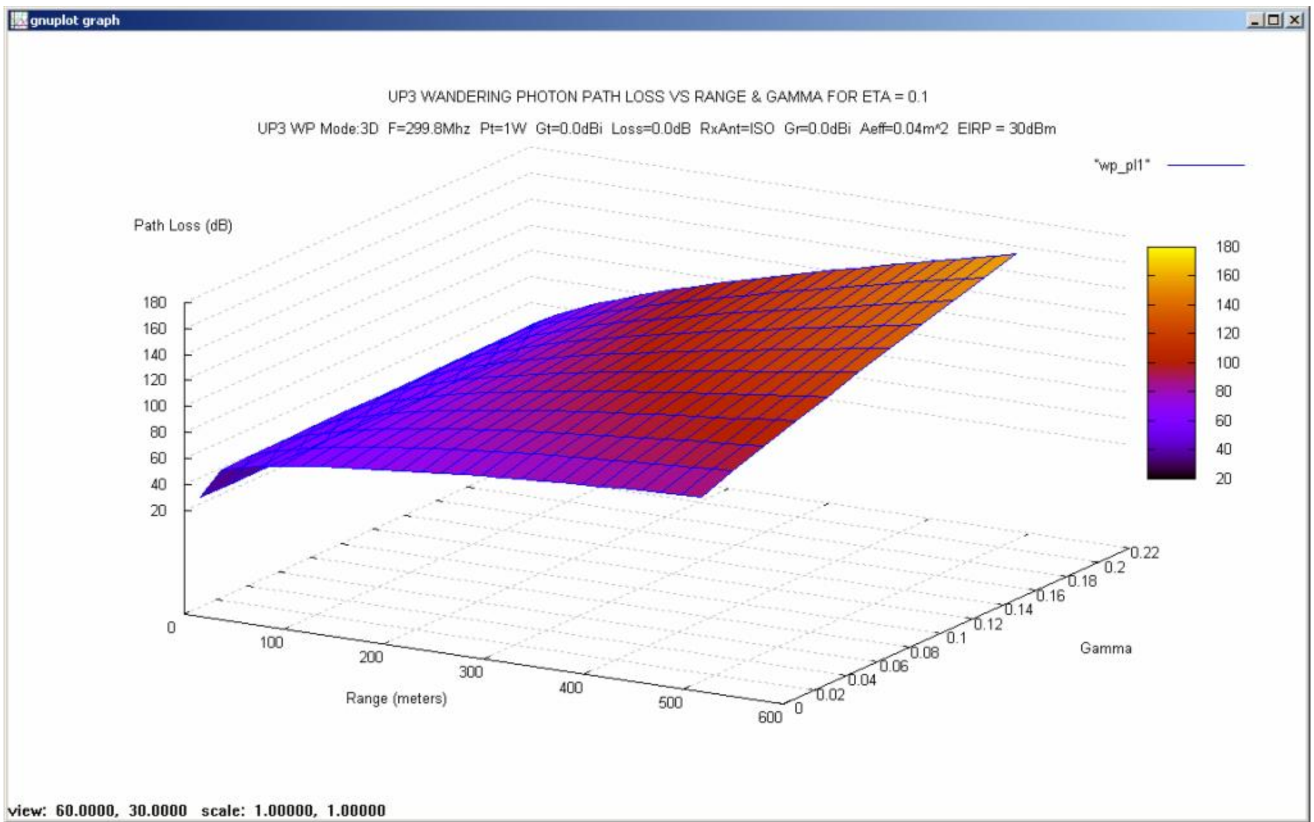

Figure 2-3: WP Path Loss vs. Range and Gamma

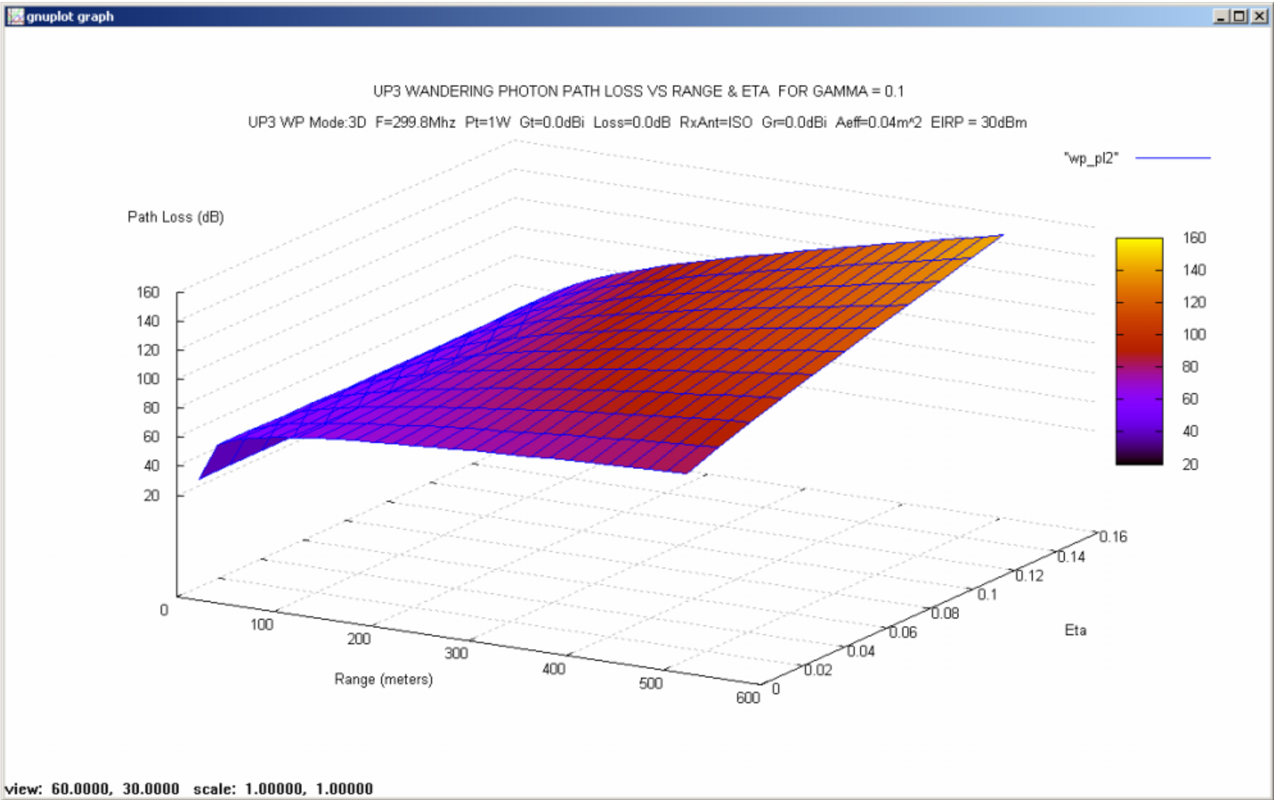

Figure 2-4: WP Path Loss vs. Range and Eta

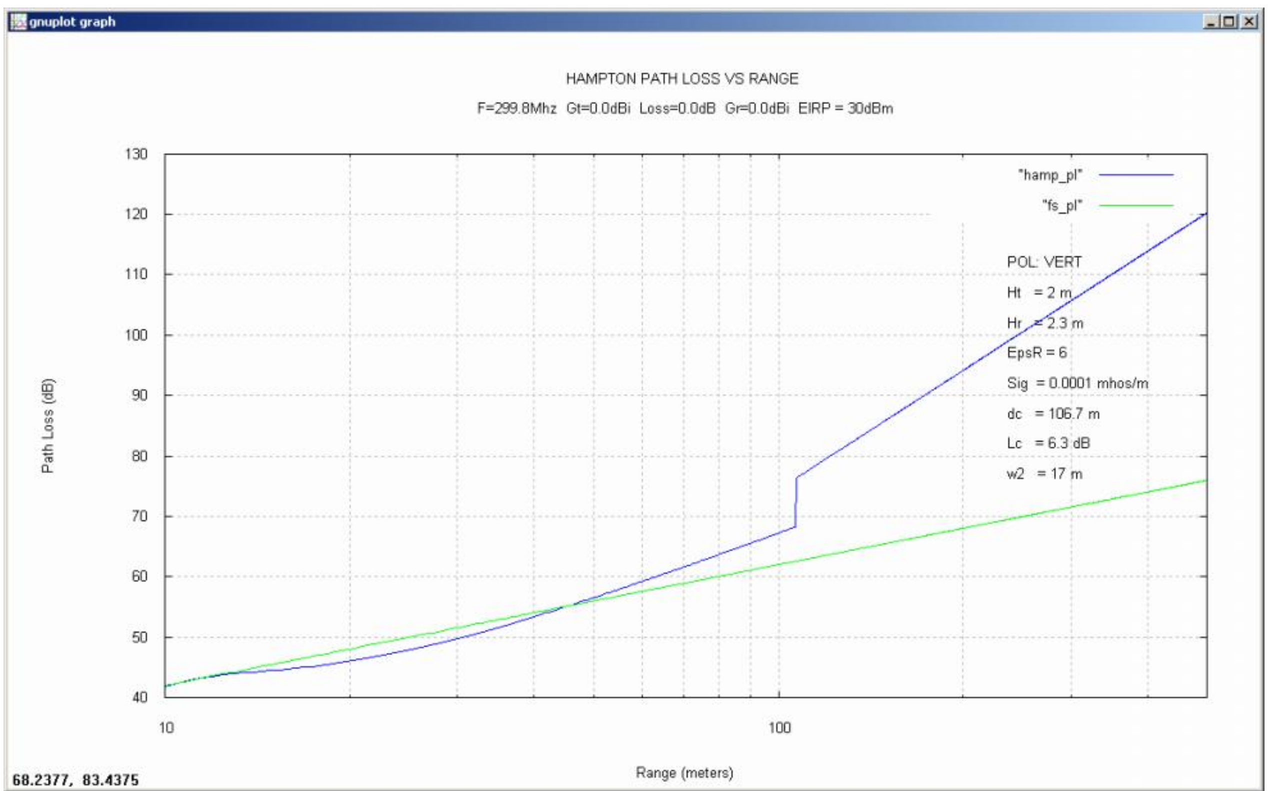

Figure 2-5: Hampton Path Loss vs. Range

CONCLUSIONS

From the work conducted to date, it has been determined that near or on-earth unobstructed and obstructed VHF/UHF paths can be analyzed using a combination of Franceschetti's Wandering Photon (WP) theory to handle obstructions and Norton's Ground Wave theory to handle the surface and space wave components. The WP method is an attractive alternative to more traditional empirical methods (due to the paucity of measured path loss data between terminals with very low antenna heights) and classical 3-D ray tracing that requires detailed environmental data describing the scatterers. In contrast the WP requires only two parameters, easily obtained from existing data bases such as: Land Use, Land Cover (LULC). The accuracy of the UGSprop code in various military environments is being determined from an extensive set of path loss measurements that began in late October, 2006 at Ft. Devens and in the city of Worcester, both in Massachusetts.

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